A radio signal has to start in an oscillator circuit, so you definitely have a "need to know"

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Before I became a Radio Amateur, I thought I knew about oscillators. After all, I had tuned many a transmitter in my Navy days, and it was a snap — set dial A to 34.9, turn on the "TUNE" switch, and adjust knob B for minimum plate current on the master oscillator. Next, tune knob C . . . etc.

The FCC exams of the day specified that you must draw a circuit diagram, and I lucked out — they asked for a neutralized-triode power amplifier. Those I knew about, because we had those in the Navy, too, and it was essential to know how to neutralize the beasts.

However, I met my Waterloo when I tried to build my first oscillator for my first ham rig. I built it "just like the book, except . . . ." It didn't work. I rebuilt, and rebuilt, and rebuilt. It didn't work. By the time I had gone through enough circuits to begin to see what was happening, or not happening, the original circuit was so out of date that I never did go back and try to make it work. But, I *did* learn about oscillators. (The next step was learning how to *stop* a circuit from oscillating, but that's a whole nuther story!)

So, here's the inside workings of oscillator circuits, presented in the hope that you'll have an easier time with them than I did, and that these words will be of some help when you find an oscillator circuit in a rig you're working on, or on your General Class (or higher) exam.

Amplifiers

No, no, I'm not off the track when I start talking about an amplifier circuit. It's just that, in order to understand what makes an oscillator work, you must first know about amplifiers. It is a fact of electronic life that an oscillator is simply an amplifier with positive feedback, *i.e.*, feedback that is aiding the original applied voltage. It is also true that, in order to sustain oscillation, an amplifier must have enough gain to overcome the losses in the circuit.

Tubes and transistors have a trait called, naturally enough, *amplification factor*. This is simply the amount by which a signal is increased as it goes through the device. You'll find a column listing the amplification factor in most vacuum-tube manuals and tables. The nearest equivalent listing for a bipolar transistor is the *beta* (β), or *current amplification factor*, sometimes expressed h_{FE} or h_{fe}. It's the ratio of base current to collector current. For example, if a transistor has a beta of 50, then 1 mA of current through the base would cause 50 mA of collector current to flow.

If you'll look at **Fig. 1**, you will see a representative ampli-

fier circuit with sine-wave drawings — one as an input signal, the other as the output. I've chosen arbitrary values to make the action easy to follow. Assuming an amplification of 10, a 1-volt input signal will produce an output voltage of 10. This is actually a variable dc voltage on the plate of the tube, caused by variations in plate current through the dropping resistor (R_p) to the plate. However, it will be interpreted by following stages (and an oscilloscope) as an alternating current (ac) voltage. (I suppose, if you really want to be picky about it, that it is an alternating-polarity voltage, because it swings both positive and negative with respect to a zero-reference point. However, convention says we've always called it an ac voltage; so be it.)

Phase

That plate resistor brings the discussion to another critical part of amplifier circuitry, which will require a bit of explanation so you can follow what is happening.

Note that the sine wave at the plate is upside-down compared with that at the grid. This is called out-of-phase. Here's why it happens that way.

The current that flows through the plate circuit of a tube is determined by the voltage on the grid. In **Fig. 2**, let's assume the tube has zero volts on the grid, and a plate current of 5 mA. This current flow through the plate resistor causes a voltage drop across it of 50 volts. This is called a "static," or nonmoving voltage; nothing is changing. Now, increase the grid voltage to +1 volt. A positive grid voltage causes more current to flow, which means that the dc voltage on the plate decreases to 40 volts. It's simple Ohm's law; $E = IR = 6\ mA\ (.006A) \times 10{,}000\ ohms = 60\ volts$. Subtract the voltage across the resistor from the plate supply, (100V − 60V) and you have 40 volts left.

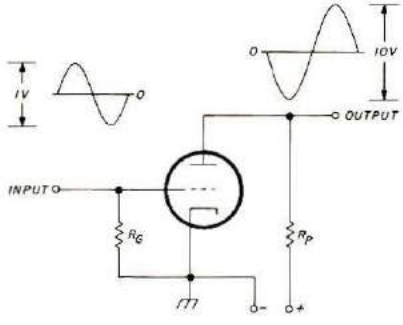

Fig. 1. An amplifier increases the amplitude of a signal applied to the grid. In addition to the increased strength (voltage) of the output signal, note that it is opposite in phase, that is, where the grid voltage goes in a positive direction, the output voltage is moving in a negative direction, and *vice versa*.

Okay, you can see that a positive voltage on the grid causes a plate voltage swing in the opposite (decreasing) direction, so let's try it for a negative voltage. Now, apply negative 1 volt to the grid. This causes less plate current to flow, which means that the voltage drop across the resistor decreases, allowing the plate voltage to climb back up, toward the positive supply voltage. Thus, you can see that the voltage on the plate always does the opposite of that on the grid (out of phase), while the current through the plate circuit follows the grid voltage, therefore is *in phase*. See **Appendix A** at the end of this article for further discussion of phase.

Feedback

Here's the trick that makes an oscillator different from an amplifier. For an amplifier to amplify, you must first give it a voltage to work with. Now, suppose you pried loose a bit of the output voltage and fed it back to the input, letting the amplifier supply its own input voltage to work on. Perpetual motion? Well, no, but self-sustaining . . . almost. As long as the gain of the amplifier is great enough to overcome any losses (resistors in the signal

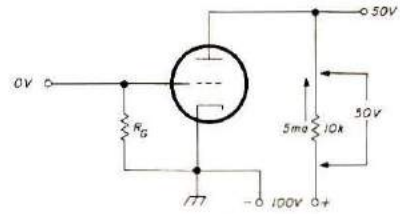

Fig. 2. For purposes of discussion in the text, an amplifier is set up in a *zero signal* condition, with zero bias on the grid, to draw a plate current of 5 milliamperes, causing the voltage drop across the plate resistor to be 50 volts. Changing the bias in either a positive or negative direction will cause a corresponding change in plate current and voltage drop across the resistor.

path, poor insulation, capacitance to ground), the signal will sustain itself, producing an output voltage, which is fed back to the grid, which produces an output voltage . . . on and on.

Just a minute! What's to keep the plate voltage from getting bigger and bigger and bigger? A thing called saturation, that's what. When the grid voltage gets negative enough to completely cut-off the flow of plate current; zero current through the resistor means a voltage drop of zero, and the voltage on the plate is now equal the supply voltage. That's as far as it can swing in that direction. When the grid is positive enough to cause maximum plate current to flow through the resistor, the voltage across the resistor is equal to the supply voltage, and the plate has zero voltage on it (well, almost zero — nothing is perfect). That's as far as it can go in that direction. At either of these two points, the amplifier is saturated; it just can't work any harder, and that's all you can get out of it.

Now, here is where things begin to get tricky: In order for the amplifier to oscillate, the voltage fed back to the grid must be in phase with what is already there. Think about it. If you have a negative voltage on the grid, causing the plate voltage to increase (in a positive direction), and take a

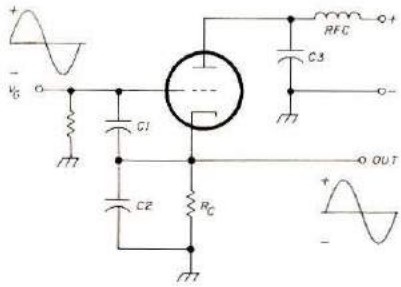

Fig. 3. One type of amplifier can be thought of as a cathode follower — the output voltage is taken from the cathode of the tube (or from the emitter in a transistor), and has the same phase as the input voltage. This feature, plus the two capacitors, C1 and C2, serving as a voltage divider, is particularly useful in one type of oscillator, as explained in **Fig. 4** and the text.

slice of that positive voltage and apply it to the grid, it'll immediately cause the plate voltage to decrease, thus turning itself off! Obviously, there's something missing here.

Reactance

That's the missing word; reactance. Now, don't get scared — it's not all that hard to understand. Reactance in an electronic circuit is pretty much the same as it is in people. It means you (or the circuit) react to a stimulus or input. The result of people reacting is often unpredictable; sometimes the action is delayed, sometimes it is the exact opposite of what was expected. Fortunately, electronic circuits are much more predictable, and they will follow the rules very closely.

Both capacitors and inductors have reactance — they oppose a change in the way things are. A capacitor causes the current to lead (go ahead of) the voltage. An inductor does just the opposite; current lags (falls behind) the voltage. Another term for what these gadgets do is phase shift — they shift the phase of the voltage or current with respect to each other. Does a spark of an idea begin to glimmer about here? How about connecting a capacitor between the plate and the grid of the tube? Introduce some phase shift, allowing the amplifier to keep itself going (oscillate).

Nope, it doesn't work. (You didn't really think it would be that simple, did you?) A capacitor shifts the phase by 90 degrees, and the plate is 180 degrees out of phase, which leaves the other 90 trying to turn the works off again. (Oh, yes, there are some circuits which will oscillate with such simple feedback arrangements, caused mostly by stray circuit defects — it's not always a dependable or predictable thing, however.)

Here's the secret: Get rid of that resistor in the plate circuit! Why? All it is doing is soaking up power, and keeping the plate at exactly 180 degrees out of phase with the grid. Put an inductance in there, or better yet, a tuned circuit (inductance and capacitance in parallel). Now, things can happen! The voltage at the plate end of the tuned circuit doesn't have to stay exactly out of phase with the grid, and if you detour a bit of the voltage and feed it back to the grid (through a capacitor with its 90-degree shift), you'll get the right kind of action through the circuit to keep the oscillations going as long as you feed power to it.

Improvements

This oscillator is pretty basic, and can stand considerable improvement. For one thing, because the plate voltage is deliberately misadjusted (with the tuned circuit) to be something other than precisely 180 degrees out of phase, it is inefficient. It also produces a lot of harmonics because of this slightly off-resonance condition. As the saying goes: "there's gotta be a better way."

There definitely is, and one of them is shown in **Fig. 3**. Note that the plate circuit now has a simple inductance in it — no tuned circuit at all. You could even put the resistor back in. That inductor, by the way, is called an rf choke (RFC). In combination with C3, it keeps any rf voltage that may be on the plate from getting into the power supply where it could cause trouble. Where's the feedback? Look at the cathode. It has a resistor connected to it, right? Note that the resistor is still in the path the current must take to get from the power supply through the tube, and back to the supply again.

That means that whatever goes through the plate also must go through the cathode, which means that the signal (a voltage change caused by varying current) will appear on the cathode too (as long as there is no big capacitor to shunt it to ground, that is).

So, just connect a capacitor from the cathode to the grid, and there's the feedback path again, you say? Golly, you're almost right. You've noticed that the phase is the same (the cathode voltage is in phase with the grid), so the feedback will help the amplifier, creating oscillations. Actually, there is no need to apply the entire cathode voltage to the grid — you would drive it into saturation right away. Let's use a voltage divider. Remember, capacitors have reactance, which appears to be resistance at radio frequencies. The larger the value of capacitance

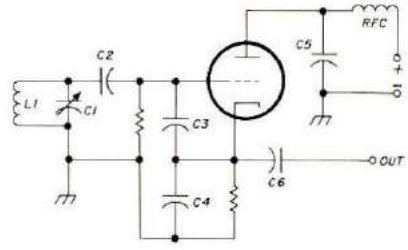

Fig. 4. In this oscillator, called a Colpitts, the feedback path is from the cathode to the grid, through C3. C4 helps limit the maximum value that the voltage can reach. The frequency of oscillation is determined by the tuned circuit L1/C1. The plate of the tube is at rf ground because of the bypass capacitor, C5. The rf choke prevents stray rf from getting into the power supply.

(bigger numbers), the smaller the apparent resistance (and vice versa). Two capacitors in series make a convenient voltage divider for rf energy, with C2 (in **Fig. 3**) shunting part of the cathode voltage to ground, and C1 feeding some of that voltage to the grid. This circuit is called a Colpitts oscillator, by the way, in honor of its inventor.

How does it know what frequency to oscillate at? Well, if you left it alone, it would work at whatever frequency was "fed back" the most efficiently, *i.e.*, with the correct amount of phase shift. Fortunately, it is easy to coerce (that's a polite word for arm-twisting) it into doing what we want — just connect a tuned circuit to the grid, as in **Fig. 4**. A tuned circuit appears to be a high resistance at its resonant frequency, but a very low resistance at all other frequencies. Any signal that was fed back to the grid, but not at the same frequency as the tuned circuit, would see what appeared as a short-circuit to ground. A signal at the proper frequency would face several thousand ohms to ground, and thus would reach the grid and be amplified.

If you change the value of the variable capacitor (C1), or the inductor (L1), or both, you'll change the frequency at which the combination is resonant, thus changing the frequency of oscillation; you've just invented a variable-frequency oscillator (VFO)!

Oscillator types

There are many different ways of providing proper feedback for an oscillator, and **Figs. 5** through **7** show some of the more common circuits. They travel by different names, usually based on the early experimenter who developed them. Some are called by different names in foreign countries because they, too, had plenty of experimenters and some of them worked on a particular circuit at the same time as Americans did. Some circuits are simply variations of a basic type, named after the guy who made a modification or improvement to the original. As an example, you might hear of a Clapp oscillator — in England it's called a Gouriet-Clapp oscillator — which is basically a modification of the Colpitts wherein the tuned circuit is arranged so that the capacitor and inductor are in series, rather than arranged in parallel.

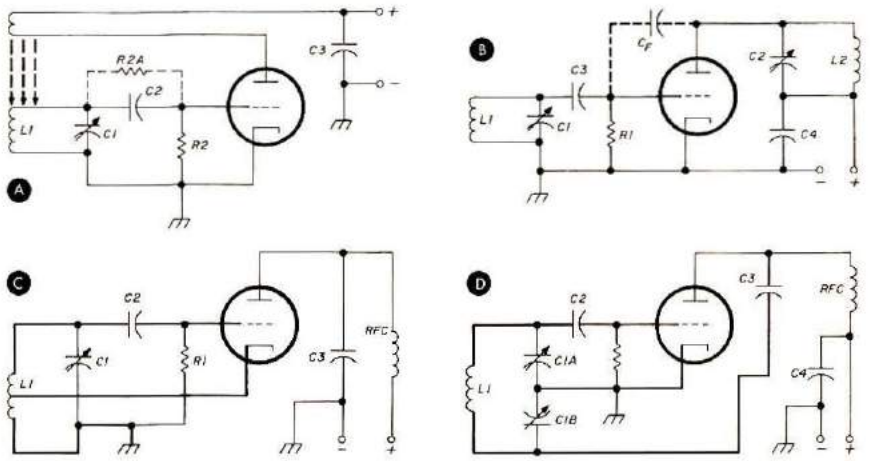

Fig. 5. Some representative oscillator types. The one at **A** is an Armstrong circuit, with the feedback path by means of magnetic coupling shown by the dashed lines between the top coil and the one to the grid. This small coil was called the "tickler," and in early receivers, the strength of oscillation could be adjusted by changing the position of the tickler with respect to the grid coil. Many circuits had the grid resistor, R2, positioned across capacitor C2 as shown by the dotted R2A — it was then referred to as a "grid-leak" resistor because it allowed a small amount of current to leak across the capacitor. Frequency of oscillation was determined by L1/C1. The oscillator at **B** is a "tuned-plate/tuned-grid" type, with the feedback path being mainly the internal capacitance from grid to plate of the tube. A Hartley oscillator is shown at **C**, with its characteristic tapped coil. The feedback path is shown in heavy lines, from the cathode, through the coil to ground. This induces current in the upper half, which reaches the grid. The Colpitts oscillator, at **D**, avoids the nuisance of a tapped coil by using the voltage-divider principle to control the amount of signal on the grid. Feedback is from the plate to the bottom of the oscillator coil.

Another version of the Colpitts is called a Vackar oscillator in some parts of the world, and a Vackar-Tesla in others. Many improvements or modifications were made in an attempt to obtain an oscillator that was more stable than the original.

At any rate, the object is to find the basic feedback path so you can identify the oscillator and understand what makes it work. The feedback is not always provided by capacitors, as you'll note in **Fig. 5A**, which is called an Armstrong circuit, and **Fig. 5C**, a Hartley circuit. The path in both is inductive, meaning that the magnetic lines of force around a coil of wire cut across another coil of wire, thus inducing a voltage across it. It's easy to follow in the Armstrong circuit, but perhaps not so obvious in the Hartley. The current from the cathode, through the lower portion of the coil, causes a build-up of lines of force, which cut across the windings above the tap point, thus providing some voltage on the grid.

Incidentally, if you're worried about remembering the names of some of these oscillators — it's not absolutely vital that you do, except as a means of impressing newcomers with your knowledge — a trick I've used is to say, "It's *hard* to tap the coil in a *Hartley*, but easy to *split* the capacitor in a *Colpitts*."

The Armstrong oscillator circuit saw a lot of use in the early days; it was a favorite for

regenerative receiver types, but is seldom seen in modern equipment.

The representative circuits I've shown here have the feedback path emphasized by heavy

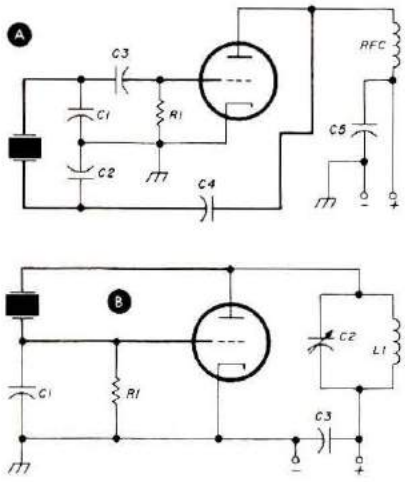

Fig. 6. Crystal-controlled oscillators use a quartz crystal in place of a tuned circuit. Shown at **A** is the familiar Colpitts circuit with the capacitors forming a feedback-control circuit. The Pierce circuit, **B**, is somewhat of a "brute force" oscillator, with the crystal connected directly from plate to grid. Some circuits use a capacitor in series with the crystal to keep plate voltage from appearing at the crystal socket.

lines in the drawings. Also, I have included a couple of circuits which are crystal controlled. A crystal is simply another means of selecting one particular frequency; it takes the place of a tuned circuit made up of a coil and capacitor.

One of the crystal-controlled circuits which has been a favorite among vhf enthusiasts for years is the Pierce, **Fig. 6B**. Note the crystal between the plate and grid of the tube. The crystal in this instance is providing the correct amount of phase shift, at the proper frequency, to allow the circuit to oscillate.

I've used tubes in the circuits talked about, mainly because it is a bit easier to follow the signal path and current flow with vacuum tubes. Some transistor circuits require tricky dc biasing circuits, and the feedback path is not always so obvious as with tubes. However, a transistorized Colpitts (note the split capacitor, C1a/C1b) is shown in **Fig. 7**.

Identification, please

All right, you've gone through some of the basic circuits, let's try to sort out a stranger. Look at **Fig. 8**. What is it?

It's crystal controlled; that's obvious. But, what is all that junk in the cathode circuit, and what are those extra grids doing there? And, what type of oscillator would you call it?

Okay, let's eliminate the forest and find a tree. There is a crystal from grid to ground, so that controls the frequency. There is a small capacitor from the control grid to the cathode, so it must be part of a voltage divider for feedback. So far, so good. How does C2 and C3 fit in? C2 is 0.001 μF, which represents 19.8 ohms at 8 MHz (the crystal frequency), therefore it is almost a short circuit for rf energy (see **Appendix B**). That means C1 is essentially connected to the top of C3, so there's the voltage divider. Aha! it must be a modification of a Colpitts. But, how about the resistor and rf choke? The resistor is in the current path through the tube, and the more current through it, the more voltage developed across it. If the voltage *across* the resistor becomes too high, the tube will not conduct (there must be an appreciable difference between plate voltage and cathode

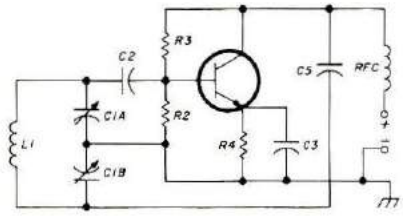

Fig. 7. In some transistorized oscillators, the type is easily recognized, as in this representative Colpitts circuit. Many of the more complex-appearing transistor circuits are really simple, but with extra components to take care of a transistor's bias, impedance, and current-protection needs.

voltage for a tube to conduct). That's it. The resistor is a biasing device, to protect the tube from overload. The rf choke seems to be a high resistance as far as radio

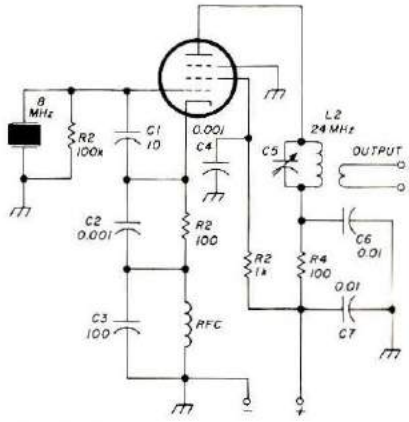

Fig. 8. This crystal-controlled oscillator has been a long-time favorite among vhf enthusiasts. It is an electron-coupled type, with the first stage of oscillation taking place in the grid/cathode circuit. The signal generated here is then coupled to the output (plate) circuit by means of the electron stream as it passes through the tube. Further details of this circuit are discussed in the text.

frequency energy goes, but is very low resistance for dc, therefore, it simply provides a dc path while letting the voltage divider (C1 and C3) handle the rf.

Okay, so far we have a modified Colpitts oscillator with cathode bias for the tube. The screen grid in a tube is there to provide some isolation between the control grid and the plate — it's sort of a shield to cut down internal capacitance. That capacitor, C4, is of the same value as the one in the cathode circuit, therefore it must provide a low-resistance path to ground for the rf signal, right? Yes, it does. The screen must be "cooled off" as far as rf is concerned, otherwise it will try to behave like a plate, and that leads to problems you don't even want to think about. That extra grid, near the plate, is called a "suppressor grid," and provides more isolation between elements.

The plate circuit — what is it doing? Well, first, it is supply-

ing a dc path to keep things going. Second, it has a tuned (resonant) circuit connected to it, and the circuit is working at three times the crystal frequency! It emphasizes the harmonic energy that is produced by the crystal-oscillator portion of the circuit, thus providing useful output on multiples of the crystal frequency. Because of the peculiar phase relationships that exist in a circuit of this type, it works out that the odd multiples are most emphasized. You can get useful output on three, five, seven, or nine times the crystal frequency. The higher the order of multiplication, the lower the power output, however. In practice, most circuits of this type are limited to a multiplication of either three or five.

So, there you have it. The oscillator is a modified Colpitts, with harmonic output at three times the crystal frequency. It has been used in many vhf rigs to obtain some of the frequency multiplication necessary for transmitters operating at 50 or 144 MHz. Oh, yes, just to cover the remaining unexplained components — R3 and R4 are in the circuit to provide a bit of over-current protection for the tube, and C6 and C7 bypass any stray rf energy to ground, keeping it out of the power supply wiring.

That's what oscillators are all about. It wasn't too difficult, really. Oh, of course there are any number of refinements that can be made to these basic circuits, but once you know what to look for it is easy to ignore the distractions. Note that I've left a lot of bias circuits and the filament (heater) connections out of the diagrams, just for clarity. These are just incidental to the operation of an amplifier with positive feedback — alias an oscillator!

Appendix A

The term "cycle" is another way of saying circle — returning to the point of start. When you push a person on a swing, you start a cycle with a push, the swing moves away, goes through an arc, swings back toward you, and you give it another push. That's one complete cycle. Electrical (and electronic) terms use degrees around a circle to keep track of the exact position of a voltage or current as it goes through a cycle, see **Fig. 9A**. The importance in being in phase or out of phase can be seen in **Fig. 9B**. Sine wave **X** starts at the zero-voltage point, moves toward the positive side, then negative, and completes a cycle. If you start sine wave **Y** just a bit later, it is said to "lag" sine wave **X** by 90 degrees. In an extreme case, sine wave **Z** is started after **X** has already completed half of its cycle — **Z** is going positive at the same time **X** is going negative, therefore **Z** "lags" **X** by 180 degrees. The two voltages cancel each other, and the net result is zero, assuming that both are of equal strength.

Appendix B

Capacitors have reactance (resistance) to alternating current energy, and it varies with frequency, that's why you cannot buy a "1-ohm" capacitor, as you can with resistors. The formula for calculating capacitive reactance is:

$$X_c = \frac{1}{2\pi FC}$$

Where F is in megahertz (MHz) and C is in microfarads (μF).

To work out the reactance of C2 at 8 MHz in **Fig. 8**:

$$X_c = \frac{1}{6.28 \times 8 \times 0.001}$$

$$= \frac{1}{0.05024} = 19.9 \text{ ohms}$$

The reactance of C2 at the output frequency, 24 MHz, is:

$$X_c = \frac{1}{6.28 \times 24 \times 0.001}$$

$$= \frac{1}{0.15072} = 6.63 \text{ ohms}$$

You can see that this valuable feature of reactance dependent upon frequency allows you to play all sorts of games with the circuit. Radio-frequency energy can be led through a circuit just the way you want, simply by providing a series of high- or low-resistance paths for it.

HRH

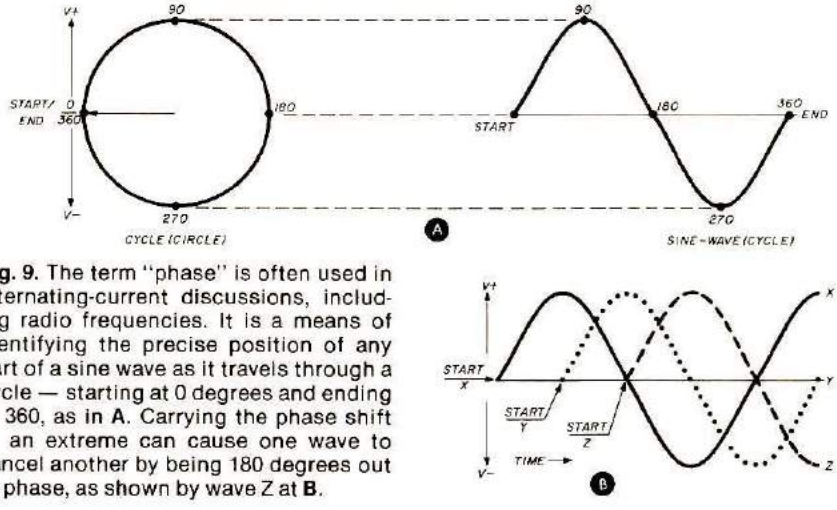

Fig. 9. The term "phase" is often used in alternating-current discussions, including radio frequencies. It is a means of identifying the precise position of any part of a sine wave as it travels through a cycle — starting at 0 degrees and ending at 360, as in **A**. Carrying the phase shift to an extreme can cause one wave to cancel another by being 180 degrees out of phase, as shown by wave Z at **B**.